

#109

ILLINOIS STATE WATER SURVEY

at the

University of Illinois  
Urbana, Illinois

RECORDING HAILGAGE EVALUATION

by

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FINAL REPORT ON RECORDING HAILGAGE EVALUATION

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National Science Foundation  
Atmospheric Sciences Section

NSF GA-1520

December, 1969

#### ACKNOWLEDGMENTS

This research was supported largely by funds from the Atmospheric Sciences Section of the National Science Foundation, NSF GA-1520. Certain data utilized were furnished at no cost by the Crop-Hail Insurance Actuarial Association and their member companies.

The work was done under the general supervision of Glenn E. Stout, Head of the Atmospheric Sciences Section of the Illinois State Water Survey. Much of the developmental work described herein was dependent upon the plans and subsequent suggestions of Dr. Eugene A. Mueller of the Survey staff. Mr. Ronald E. Rinehart assisted in the laboratory testing and calibrations. Several other Survey staff members assisted in the developmental and construction phases of the project including Edward Silha, Ronald Tibbetts, and James Harry. Mr. Dean Timme installed and performed the field operations of the hailgage during 1969, and Mr. John Hornaday measured crop-hail losses. Student employees who assisted in the hailgage construction, particularly of the electronic components, included David Brunkow, Earl Payne, Kenneth Downs, and Robert Polivka.

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## INTRODUCTION

This is the final report to the National Science Foundation for the recording hailgage evaluation project, NSF GA-1520. The grant was awarded 1 April 1968 and was terminated on 31 October 1969.

A recording hailgage was designed and a prototype constructed as a part of the hail research activities during 1966-1968 on NSF GA-482, the Hail Evaluation Techniques project. The operational potential shown after laboratory and brief field testing indicated a requirement for further field evaluation under several natural hailfalls.

A recording hailgage of this type which records information on the individual hailstone momenta, size, and time with great accuracy has application in several research areas. These include general studies of surface hail parameters,<sup>1</sup> hail suppression projects,<sup>2</sup> research concerning which parameters damage crops,<sup>3</sup> and studies on the time-size distributions of hailstones<sup>4</sup> for calculations of radar reflectivity from hail.

The many useful applications of the data obtainable from such an instrument were sufficient to warrant its further field evaluation. The primary objective was to determine whether the gage-measured hailfall parameters (momentum and stone size) were relatable to measured crop damages, and of course, as a major consideration, to improve the field operation of the instrument beyond that of the prototype. This primary goal meant that the instrument should be installed in rural areas and immediately adjacent to the basic crop types of Illinois--corn, soybeans, and wheat. Since the average point hail-day frequencies are three per year in most of Illinois, securing sufficient samples to obtain a proper evaluation of the instrument

in a reasonably short time could be accomplished only by construction of several such instruments to be operated simultaneously in a network array. This would greatly improve the opportunities for hailfalls on the instrument, evaluation of its performance and data, and collection of data that can be correlated with radar data.

The project called for the construction of 15 hailgages plus field testing in an 18-month period. The construction phase required 13 months. Eleven of the completed gages were installed in a network array in central Illinois in June 1969 and were removed from operation on 31 October 1969. Unfortunately, no hailfalls occurred at any of the gage installations during this 5-month operational period. However, these field operations furnished information useful for improving the instrument design.

The text of this report is composed of six sections. The first provides a detailed description of the design and construction of the hailgage, and the second describes their installations and operations in 1969. The third section of the report concerns a study which, although not planned in the original proposal, was performed as a part of this project. This additional study consisted of laboratory testing and operation of two other recording hailgages, one constructed by NCAR and the other by the South Dakota School of Mines and Technology. The fourth section of this report presents information on hailfall characteristics and crop-loss data as derived from passive hailpad data; these comparative studies were performed largely because of the lack of hailfalls on the recording hailgages. The final section includes a summary and recommendations for the instrument and a list of published and unpublished papers concerning the project activities.

## HAILGAGE DESCRIPTION

### Design Theory

The instrument design was based on the ballistic pendulum principle since this type of mechanical device appeared to offer the best economical solution for measuring momentum of individual hailstones.<sup>5</sup> In the device designed, the hailstone is allowed to impinge on a horizontal mesh screen of stainless steel. This horizontal platform (Fig. 1a) is constrained to move only in a vertical direction by linear-travel ball bearings. The platform is balanced by a pulley system and a counterbalance. The extent of travel of the platform is determined by the change in momentum of the impinging hailstone and the mass of the platform and counterbalance, and the restoring force is produced by the restoring cam and weight. The amount of travel is recorded by a lever arm on a cylindrical record.

The momentum of a 0.5-cm hailstone is approximately  $2 \times 10^2$  gm cm/s, and that of a 5-cm stone approximately  $2 \times 10^5$  gm cm/s. Because of this large range of momentum for which measurements are desired, a restoring force that increases rapidly with increased displacement is required.

The equation of motion of the platform may be expressed as:

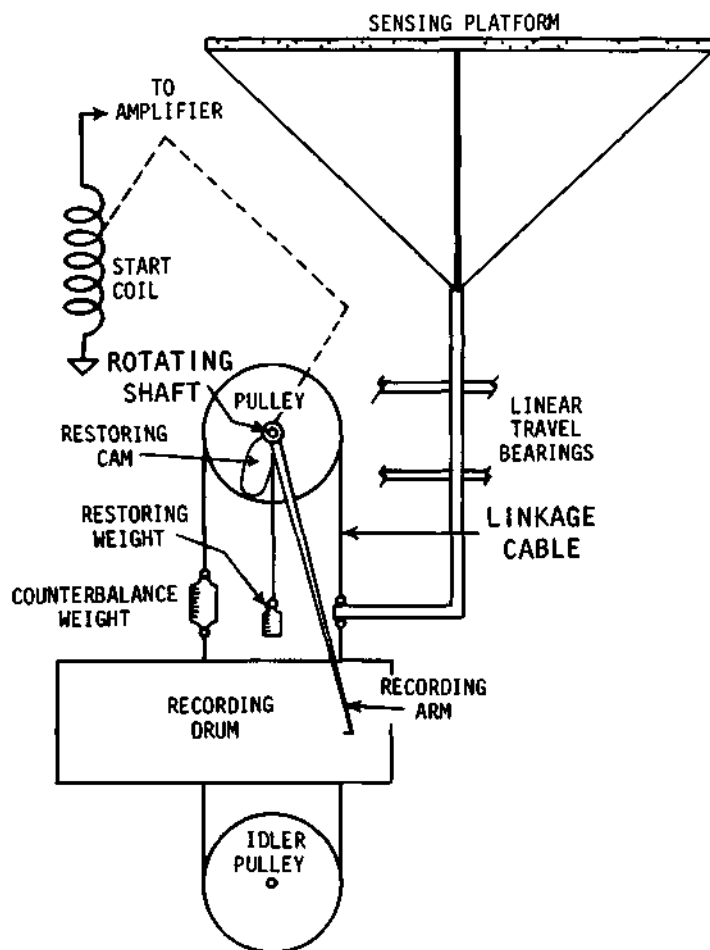
$$m \frac{d^2 x}{dt^2} = -F_0(x) \quad (1)$$

where

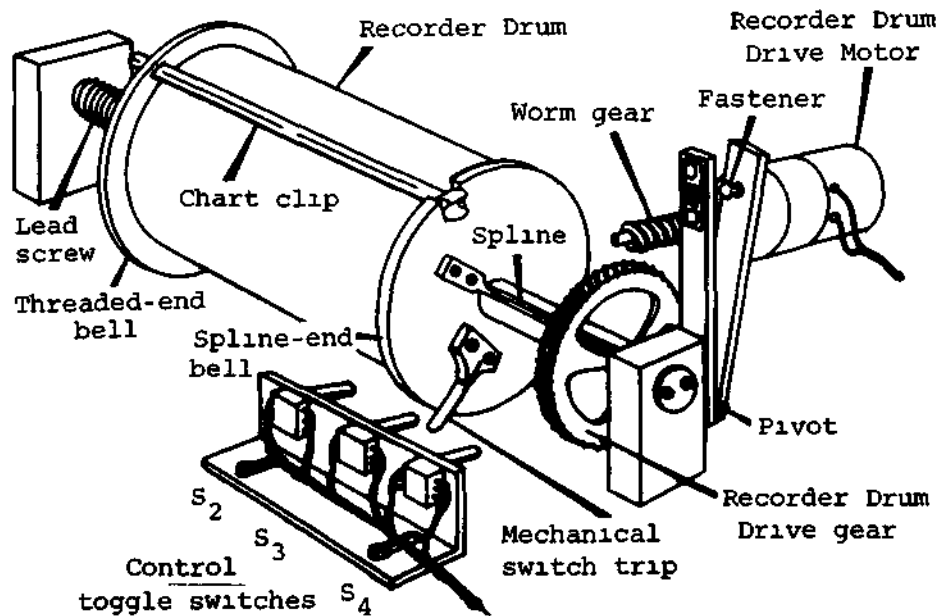
$m$  = mass of the platform and counterbalance

$x$  = the linear displacement of the platform measured  
from the initial "at rest" position

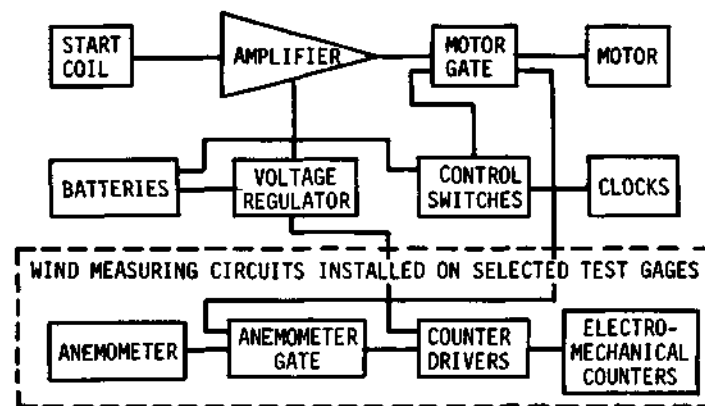
$F_0(x)$  = the force produced by the restoring cam and weight  
as measured at the sensing platform



a. Hailgate mechanical diagram



b. Recording drum and drive motor



c. Block diagram

Figure 1. Hailgate diagrams

The implicit assumptions in this equation are that frictional effect of the bearings and pulleys are neglected; that moments of inertia of the pulleys, recording arm, restoring weight, and cam (Fig. 1a) are negligible with respect to the moment inertia of the platform and counterbalance weight; and that the platform is completely rigid and flat.

If  $\frac{dx}{dt} = v$ , velocity of the platform, equation (1) becomes

$$v \frac{dv}{dx} = - \frac{F_o(x)}{m} = -F(x) \quad (2)$$

Integrating (2) results in

$$v = [-2 \int_o^x F(s) ds + C]^{1/2} \quad (3)$$

The constant C can be evaluated by considering the conservation of momentum and evaluating the momentum of the entire system (hailstone and platform) just before collision and just after collision. Since a body may impinge with either an inelastic collision (sticky collision) or an elastic collision (bounce), the change in momentum of the hailstone varies from  $m_s v_s$  to  $2 m_s v_s$ , where  $m_s$  is the mass of stone and  $v_s$  is the vertical velocity of the stone. -The actual momentum change will vary with the characteristics of the hailstone (i.e., hard and dry or soft and spongy). In practice, it is probable that the actual change in momentum will be intermediate to the elastic and inelastic collision.

If the change in momentum of the hailstone is represented by I (the impulse), then the conservation of momentum implies that the measured impulse is  $I - mv_o$ , where  $v_o$  is the velocity of the platform just after impact. The



constant C can then be evaluated for  $x = 0$ , so that  $I^2/m^2 = C$  and equation (3) becomes

$$v = [-2 \int_0^x F(s) ds + \frac{I^2}{m^2}]^{1/2}$$

The point of maximum travel,  $x_m$ , occurs at the time at which the velocity becomes zero. This follows since the velocity is the time derivative of the displacement and maximums are usually found by setting the derivatives to zero. Thus equation (4) becomes

$$\int_0^{x_m} F(s) ds = \frac{1}{2} \frac{I^2}{m^2} \quad (5)$$

In general, little information on the time response of this instrument can be obtained from this analysis. For the harmonic case, where  $F(x) = kx$ , the time constant can be determined and is not a function of the magnitude of  $I$ . However, it is easily seen that  $x_m$  is proportional to  $I$ , and, as previously mentioned,  $I$  ranges over 3 orders of magnitude. Thus, if a 1 mm deflection occurs with a 0.5-cm hailstone, a deflection of over 1 mm occurs with a 5-cm hailstone. The mechanical recording of such a long range would be very difficult.

Therefore a restraining force that increases more rapidly with displacement was sought. Since the final calibration (Fig. 2) of the device was to be for stone diameter, an attempt was made to make the deflection versus stone diameter as linear as possible. The form of the function chosen was

$$F(x) = \frac{k}{m} (e^{ax} - 1) \quad (6)$$

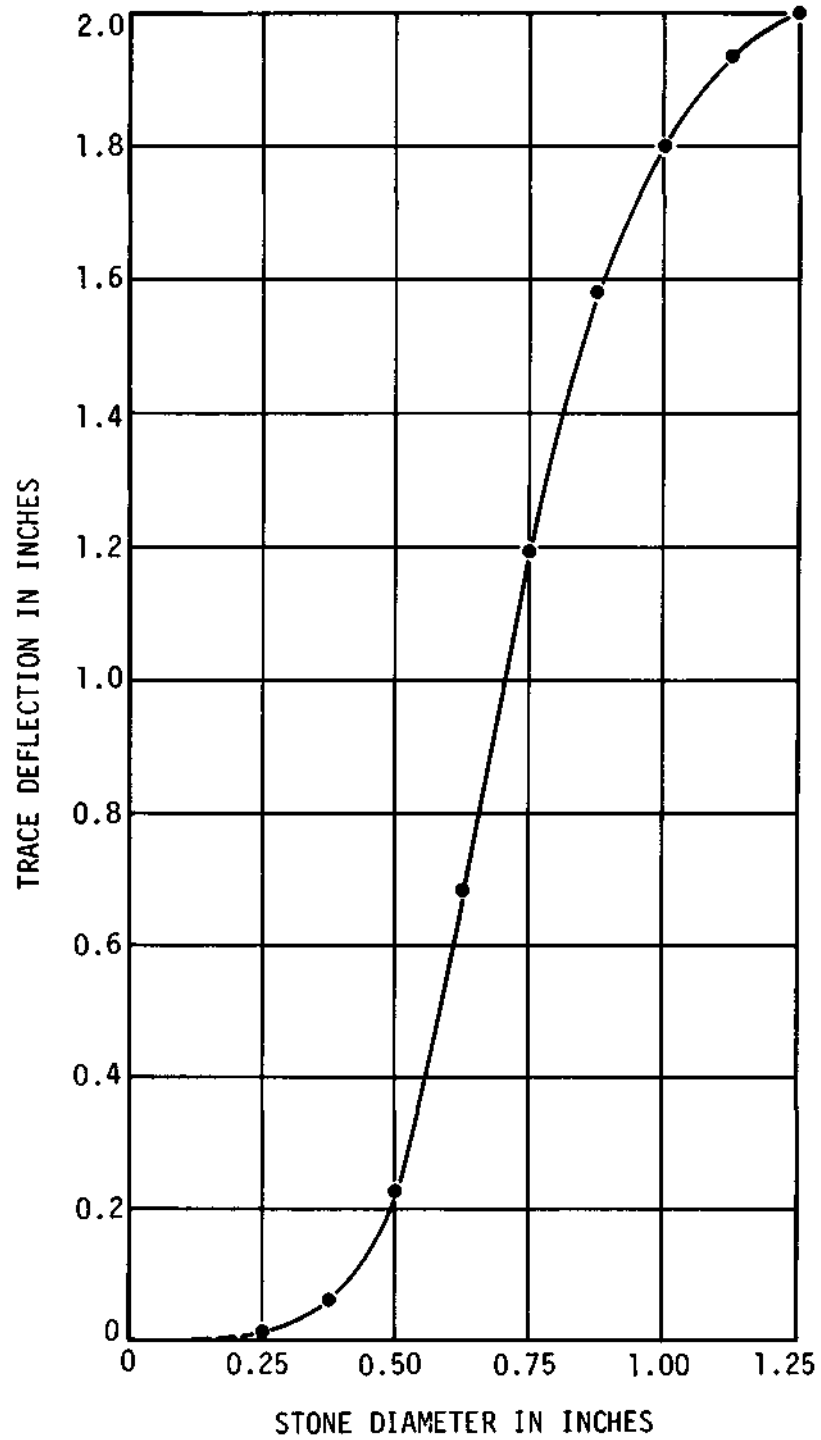


Figure 2. Calibration curve for hailgage #13

Integration of this function yields an equation relating the maximum deflection to the impulse I, the mass of the platform and counterbalance m, and constants of the restoring force a and k.

$$\frac{e^{ax_m}}{a} - x_m = \frac{1}{a} + \frac{1}{2} \frac{I^2}{m^2} \quad (7)$$

The angle, Q, through which the pulley and cam rotate is related to the linear displacement, x, by  $Q = x/r_p$ , where  $r_p$  is the radius of the pulley.

By using equation (7) with the maximum and minimum limits of travel along with the impulses appropriate to these travels, two equations with a and mk as unknowns were determined. The two equations were solved numerically by means of an IBM 7094 computer equation program. The equations are extremely sensitive to values of a. The results computed with the 7094 were used to select the final dimensions which are shown below.

$r_p$  (pulley) = 1.2 inches

r (recorder arm) = 6 inches

chart deflection maximum = 2.75 inches

chart deflection minimum = 0.05 inches

The form of the cam and mass of the restoring weight were calculated using these dimensions by straightforward mechanical and trigonometric equations.

### Theory of Operation

The basic concept of the hailgage is to mechanically link and record a vertical sensor displacement as an amplitude deflection on a motor-driven recording chart which incorporates a constant speed drum drive to provide an accurate time scale for the hailfall record.

A rotatable shaft (Fig. 1a) supported by ball bearings has a pulley, restoring cam and weight, recording arm, and start magnet securely attached so that any angular movement of one component will result in the same angular movement of all other components attached to the shaft. A cable attached to the circumference of the pulley supports the sensing platform from the right of the pulley and the platform is held in equilibrium by a counterbalance of equal weight hanging from the left of the pulley. A restoring weight attached by a steel cable to an eccentric cam is positioned so that when at the normal rest (inoperative) position the cam is applying no rotational force to the shaft. However, with the first downward movement of the sensing platform, the resulting counter-clockwise movement of the restoring cam causes the restoring weight to apply an opposing rotational force. This opposes the downward movement of the sensing platform and returns the platform to its original position after the momentum of the platform has deflected the pulley through its maximum angular displacement. The recording arm, which is attached to the rotatable shaft, is positioned on the right of the recording drum with the writing stylus in contact with the drum at the point of tangency (Fig. 1a).

A recording cycle consists of the recording drum rotating through 12 revolutions at the rate of  $1\frac{1}{6}$  revolution per minute with a uniform horizontal movement of  $\frac{1}{12}$  inch per revolution.

The recording drum drive motor is started with a pulse generated by the movement of the permanent magnet of the rotating shaft. After 12 revolutions the recording drum has moved 1 inch to the right (Fig. 1b), and tripped a switch that stops the drive motor and starts the timer associated with that cycle. The clock, which runs until the gage is serviced, is used in conjunction with the actual time the gage is serviced to determine accurately

the ending time of the first hailfall. This hailfall cycle can be repeated two more times giving the possibility of recording 3 separate hailfalls, each with a duration of 10 minutes or less. Since the time between the end of a one hailfall (cycle) and the time when a new one starts may be only milliseconds, or assuming the hailfall would continue for longer than 10 minutes, the record would thus be continuous to the maximum of 30 minutes.

After service personnel have placed the control switches (Fig. 1b) to the "operate" position, electrical control of the motor to advance the recording drum is achieved by rotating a permanent magnet in the start coil (Fig. 1c), amplifying and shaping the pulse with an integrated circuit amplifier, and using this pulse to "set" an SCR (Silicon Control Rectifier) to the "on" condition. After 10 minutes, using the accurately controlled recording drum speed as a timer, the drum mechanically trips a control switch which "sets" the SCR to a non-conducting state, initiates the clock operation associated with the cycle, and resets the gage for the next 10-minute cycle.

The trace is recorded by a sapphire stylus scribing a wax coated paper manufactured by Graphic Controls Corporation, type: Blush film coated pressure sensitive chart paper, Code 92, P-110 paper, 6-3/8 inches wide x 13-1/4 inches long.

## Fabrication

Platform. The 12-inch diameter sensing platform (see Fig. 6b) is constructed of #30 mesh, 0.01-inch type 304 stainless steel wire cloth cemented (epoxyed) to a 12-inch diameter hoop of 1/4-inch magnesium alloy. Eight straight sections of aluminum alloy, each 1/8-inch diameter by 7-1/2 inches long, are symmetrically spaced and epoxyed from the rim of the platform to a center post which mates with

the 1/4-inch diameter linear travel shaft. This type of construction represents a compromise of rigidity, low mass, and low cost that is easily fabricated.

Recording Arm. The recording arm is constructed of an 0.020-inch thick piece of tempered bronze which acts as the spring applying writing pressure. It is 6 inches long and uniformly tapered from 1/2-inch wide to 5/16-inch wide at the writing point (Fig. 1a). The writing point is a sapphire stylus of 0.015-inch diameter, 0.075-inch long, and 5 mil radius epoxied to the metal. It is adjusted for 5 grams pressure on the pressure sensitive paper used to make the hailfall record. Adjustment of the scribing pressure is achieved by moving the recording arm perpendicular to the recording drum.

Recording Drum. The recording drum (Fig. 1b) was constructed from brass tubing 3.5-inch OD, with 0.065-inch wall thickness, cut to 6-1/2 inches in length. End bells fabricated to mate with this tube and to accept a chart clip gave a usable chart size with a 6-inch width and a 11-inch length.

The non-driven end bell (on left, Fig 1b) contains a 9/16-inch x 12 NC internal thread which is mated with a stationary 9/16-inch x 12 NC threaded shaft to provide support and the "lead" advance as the drum is rotated. The other end bell was adapted to mate with a splined bushing which provides drum support, permits direct rotational coupling of the drum to the drive motor, and at the same time permits the drum to advance at the "lead" generated by the thread of the other end bell.

A 24-volt DC, 30 rpm, chronometer-regulated drive motor containing a worm drive gear is mounted on a pivot and clamped in position to engage with the drive gear of the recorder drum (Fig. 1b). The 30-rpm motor coupled

through a 25:1 gear ratio gives a drum speed of 1-1/16 rpm or a chart rotation every 50 seconds.

Frame. The frame is constructed on a 20-inch diameter, 5/8-inch thick, cast aluminum base plate (see Fig. 4). A three-legged, 7-inch high platform is attached to support the upper platform, the rotating shaft, the start coil, and the lower linear travel bearing. The upper platform, which is the upper linear travel bearing support, is formed by a Y-shaped, aluminum casting supported on three aluminum columns of 3/4-inch diameter and 5-inches in length. The upper support also has a funnel and hose attachment which collects and drains the water from the platform stem and linear travel shaft. All other components are attached to the base by machine screws mating with threaded holes.

Cover. The cover is fabricated from 0.050-inch thick, type 5052 H34 aluminum alloy sheet metal. The outside walls are formed by rolling and welding a 63- x 28-inch sheet into a 20-inch diameter cylinder. A crimp on the wall of the 20-inch diameter cylinder, 15 inches from the bottom, supports a top formed in the shape of a 140° cone with a 1-inch diameter hole at the apex of the cone for the passage of the linear travel shaft. Weather-proofing of the top-sidewall joint is accomplished by calking the joint with silicone rubber sealant. The cover is placed on the gage with the sensing platform removed from the linear travel shaft, and the cover is secured to the base plate with three Sealco fasteners.

Clock Assembly. Evaluation of battery-operated clock movements determined that the Elgin type 085 movement was a desirable compromise of economy and accuracy to record the lapse time from the end of hail to actual servicing.

A motor-wound spring drives the clock escapement, and since the spring requires 8 minutes to unwind, the service man would have to spend this time at the gage before resetting the clocks. To prevent this delay in servicing, the clocks were mounted on a panel (Fig. 4, top center photo) with an Amphenol type 133-018-21 jack riveted to the bottom of the panel which mated with an Amphenol type 143-018-01 socket serving both as a support and as the electrical connections for the clock assembly. Having this standardized "plug in" clock assembly and providing one extra assembly permitted the service man to be traveling to the next gage while the clock springs were "running down."

#### Electronic Design and Components

The rotating shaft (Fig. 1a) has a small permanent magnet attached to it which rotates, generating a pulse in the start coil (Fig. 3). This pulse is amplified and shaped by all 3 stages of a type CA 3035 integrated circuit. At this time, the amplified pulse turns the SCR (C 106Y1) on, completing the 24-volt battery circuit through the motor and the start positions of  $S_{2a}$ ,  $S_{3a}$ , and  $S_{4a}$ . After 12 revolutions of the drum (10 minutes), the drum mechanically switches  $S_{2a}$  from the start to stop position. This momentary interruption stops the conduction of the SCR, preventing the motor from running until another hailstone impact occurs. Clock  $C_1$  has a ground applied through  $S_{2b}$ , completing the clock circuit which continues to run until reset by an operator.

After the completion of the first 10-minute cycle, the next hailstone falling on the sensing platform starts a second 10-minute cycle which is gated on in the same manner and ended by the drum switching  $S_{3a}$  from the start to stop position.  $S_{3b}$  activates Clock  $C_2$  which continues to run until reset by the service personnel. The third cycle is identical to the first two, except





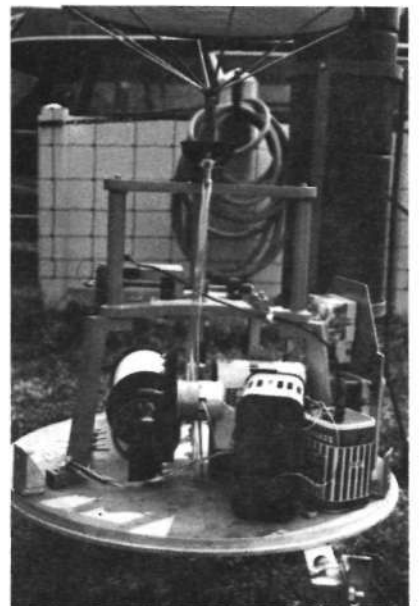
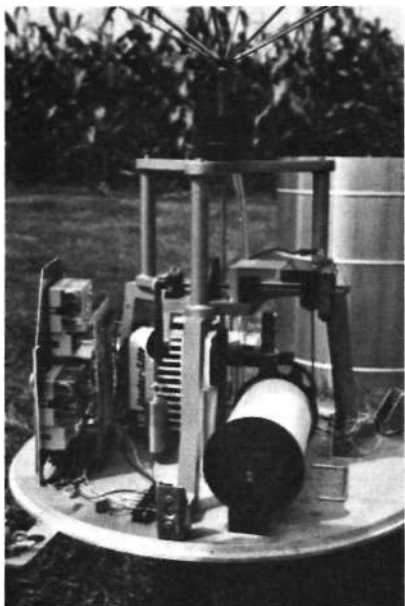
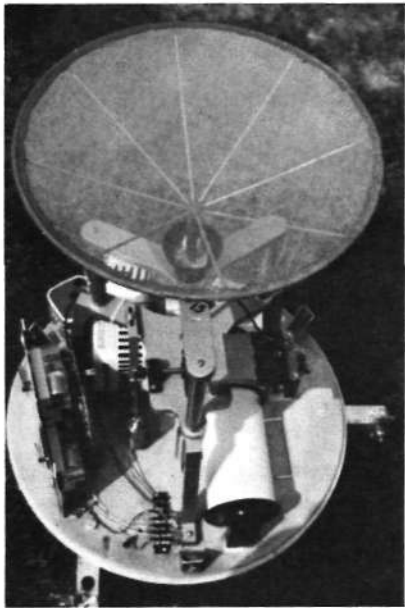


Figure 4. Various views of the hailgauge with outer cover removed

that at the end of the third cycle  $S_{4a}$  disconnects the 24-volt battery until the gage is serviced.

The 6-volt battery is stabilized to a nominal value of approximately 4 volts by using the junction voltage of  $Q_1$  as a reference for comparison with the portion of the voltage output developed across 2.2 k in series with 12 k. The voltage difference is amplified and applied to  $Q_2$  and  $Q_3$  which act as a regulating element to provide a stable voltage for the CA 3035 until the battery voltage decreases below 4 volts.

Hailgage parts and labor used in fabrication are listed in the following Tables.

#### Hailgage Parts List, Electrical

Quantity	Description	Mfg Type	Unit Cost	Cost
1	Battery, ( $B_1$ ) 6v	Burgess F4BP	.99	.99
1	Battery, ( $B_2$ ) 24v (use 2ea-12v)	Burgess TW2	1.96	3.92
1	Battery, ( $B_3$ ) 1.5v	Eveready 935	.15	.15
1	Capacitor, 500 uufd	Centralab Type CE 501	.07	.07
1	Capacitor, .005 ufd	Centralab Type CE 502	.08	.08
2	Capacitor, Electrolytic, 5 ufd, 6v	Sprague Type TE 1084	.17	.34
3	Clocks, 1.5-volt movement	Elgin Type 085 movement	5.75	17.25
1	Coil, starting - 1500 turns #40 enameled magnet wire wound on 1" square bobbin			
1	Connector, Clock, jack	Amphenol Type 133-018-21	2.26	2.26
1	Connector, Clock, socket	Amphenol Type 143-018-01	1.20	1.20
1	Connector, Plugboard socket	ELCO Type 5009	1.83	1.83

Hailage Parts List, Electrical (cont'd)

<u>Quantity</u>	<u>Description</u>	<u>Mfg Type</u>	<u>Unit Cost</u>	<u>Cost</u>
1	Diode, IN270	Sylvania	.11	.11
1	Diode, IN2482	Sarkes-Tarzian	.27	.27
1	Integrated Circuit, 3 independent general purpose amplifiers	RCA Type CA 3035	1.80	1.80
1	Magnet, Bar 3/4" x 3/8" x 3/16"	Eclipse #844	.13	.13
1	Motor, 24v DC, 30 rpm	A. W. Haydon DC Timing Motor with Chronometer Governor	*94.00	94.00
1	Plugboard, electronic circuit board	Vector 812 with ELCO contacts	2.68	2.68
11	Resistor, 330 1/4 w	Ohmite Type RC07GF	.07	.77
3	Resistor, 4.7k, 1/4 w	Ohmite Type RC07GF	.07	.21
1	Resistor, 1k, 1/4 w	Ohmite Type RC07GF	.07	.07
1	Resistor, 2.2k, 1/4 w	Ohmite Type RC07GF	.07	.07
1	Resistor, 6.8k, 1/4 w	Ohmite Type RC07GF	.07	.07
1	Resistor, 12k, 1/4 w	Ohmite Type RC07GF	.07	.07
1	Resistor, 15k, 1/4 w	Ohmite Type RC07GF	.07	.07
1	Resistor, 22k, 1/4 w	Ohmite Type RC07GF	.07	.07
1	Resistor, 100k, 1/4 w	Ohmite Type RC07GF	.07	.07
1	Resistor, 680k, 1/4 w	Ohmite Type RC07GF	.07	.07
1	Resistor, 50k variable, 1/4 w	CTS Type R503B	.35	.35
1	Silicon Control Rectifier	G.E. Type C106Y1	.63	.63
1	Switch, S <sub>1</sub> , SPST	Alco Type 105D	1.12	1.12
3	Switch, S <sub>2</sub> -S <sub>3</sub> -S <sub>4</sub> , DPDT	Alco Type 215N	1.43	4.29
3	Transistor, 2N4400	Motorola	.40	1.20

\*Available military surplus @ \$12.50/unit

### Hailgage Parts List, Mechanical

<u>Quantity</u>	<u>Description</u>	<u>Mfg Type</u>	<u>Unit Cost</u>	<u>Cost</u>
2	Bearings, Shaft	New Departure Type 77R4	1.47	2.94
2	Bearings, Linear	Thompson A-4812-SS	7.15	14.30
1	Castings, Set	Leach Casting Hailgage Pattern 1		43.50
1	Gear, Motor Worn	Browning Gear W32-4H	6.22	6.22
1	Gear, Recording Drum Drive	Browning Gear DWG32100-4	7.99	7.99
1 Lot	Material necessary for fabrication of gage (metal, plastic, screws, wire, fasteners, epoxy, and aircraft cable)			23.69

### Hailgage Fabrication, Labor

<u>Total Time</u>	<u>Personnel Classification</u>	<u>Unit Cost</u>	<u>Cost</u>
84 hours	Laboratory Mechanic (fabricate assemble, and finishing)	3.85	323.40
4 hours	Engineering Student (wiring and assemble circuit board)	2.00	8.00

### Wind Measuring Equipment

Prior experience in relating hailstone size and density to crop losses has indicated the possible importance of surface wind as a factor in crop losses during hailstorms. To determine if the measurement of total wind during the recording period would provide useful information we added the wind measuring circuits (Fig. 1c) to four gages.

In concept, the wind totalizing circuit uses a modified Stewart No. 401 4-cup anemometer to provide pulses which are counted by three counters during the

first recording period. After the first recording period, counter 1 is removed from the circuit and counters 2 and 3 accumulate the additional pulses generated during the second recording period. After the second recording period, counter 2 is removed from the circuit and counter 3 accumulates the additional pulses generated during the third recording period. Therefore, the wind total for hail period 1 is the reading of counter 1; the wind total for hail period 2 is the reading of counter 2 minus the reading of counter 1; and the wind total for hail period 3 is the reading of counter 3 minus the reading of counter 2.

The Stewart No. 401 4-cup anemometer was modified by removing the gear train, attaching a permanent magnet to the shaft driven by the cups, attaching a dry reed switch so that it operates on each rotation of the cups, and adjusting the cups for 16-cup rotations (switch closures) each 1/60 mile of wind passage.  $Q_7$  and  $Q_8$  (Fig. 3) shape the pulse to operate a 4-bit counter (2 - Motorola MC890-P integrated circuits) which gives one pulse output for each 1/60 mile of wind passage.

$Q_9$  through  $Q_{14}$  using the output of the 4-bit counter forms a single pulse for each 16 revolutions of the anemometer cups. This pulse is sufficient to drive the three Mercury, four-digit, 24-volt DC coil (33 BC6), electric impulse counters used as wind indicators. The circuit is designed for a minimum pulse width to reliably operate the counters at 24 volts, and the pulse width automatically increases as the battery voltage decreases giving reliable operation until the battery terminal voltage decreases to 16 volts.  $Q_4$ ,  $Q_5$ , and  $Q_6$  remove most of the circuit power during non-operating periods, except at the end of the third period when the ground applied to the base of  $Q_2$  removes most of the circuit power.

## HAILGAGE INSTALLATIONS AND OPERATIONS

### Location

Thirteen hailgages were completed and tested by 15 June 1969, and these were immediately field-installed. As shown in Fig. 5, 11 of these gages were arrayed within the 1600-sq mi hailpad-raingage network operated by the Water Survey. The 12th hailgage was installed at the local Urbana weather station operated by the Illinois State Water Survey because it could be routinely observed and checked by our weather observer. It was also located within 20 feet of a University of Illinois corn test area. The 13th completed gage was installed on the roof of the Water Resources Building in Champaign, so that its operational performance could be closely observed by project personnel. Two of the 15 planned hailgages were not field-installed because certain components were not delivered until the fall of 1969.

Each network hailgage was placed at a raingage-hailpad site and installed using three 1-inch angle iron stakes driven 18 inches into the ground. The typical installation at four of the 11 network sites is shown in Fig. 6. The recording raingages at all sites had been modified (evaporation funnel removed) so as to record time of hail,<sup>6</sup> and the hailpads furnished hail data for comparison with any hailgage data.<sup>7</sup>

### Data and Operations

The hailgages were located very close to growing crops so that if damaging hail occurred, a crop loss value could be determined for comparison with the hailgage data. A professional hail adjustor was employed during the mid-June through September 1969 period on a part-time basis. One of his

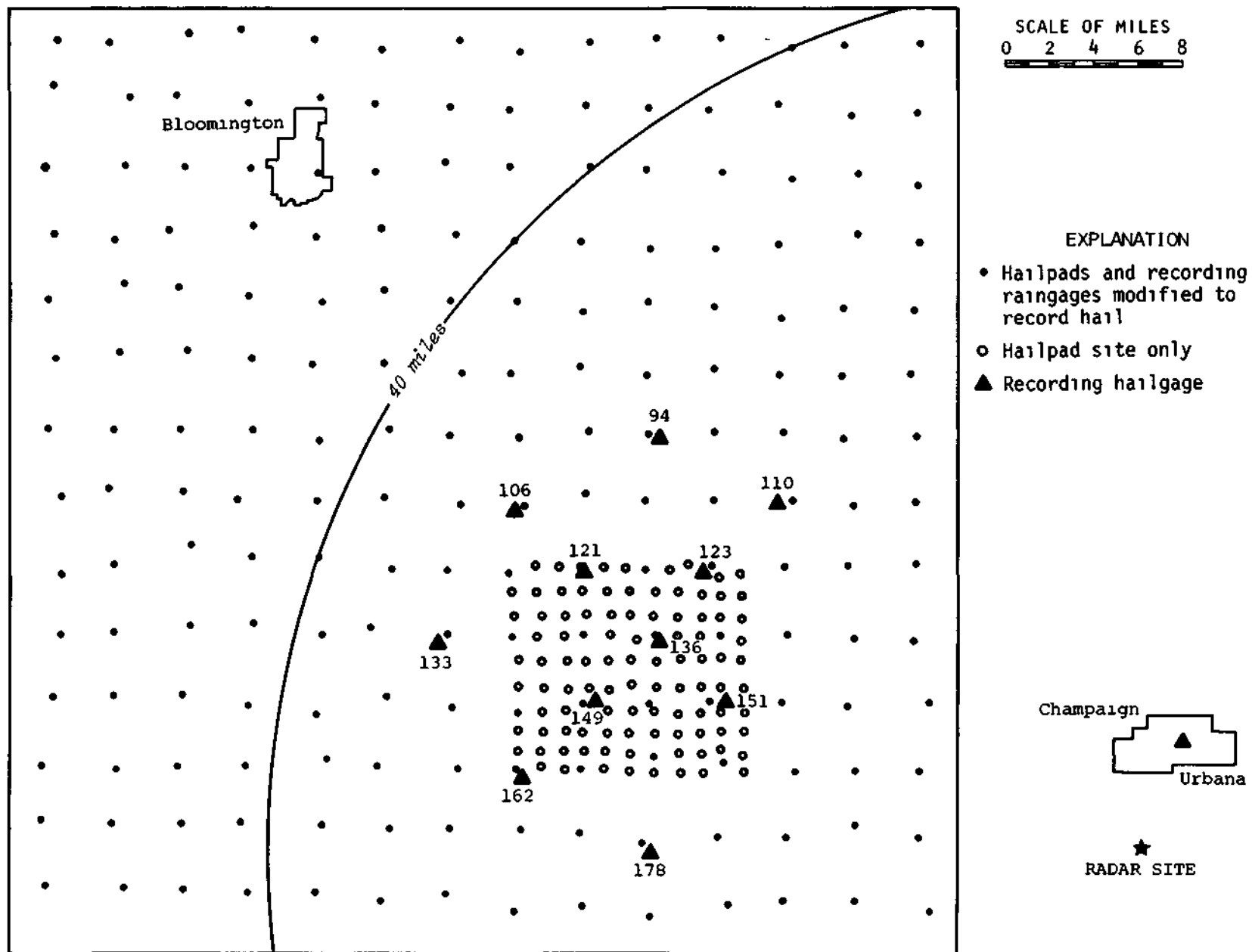
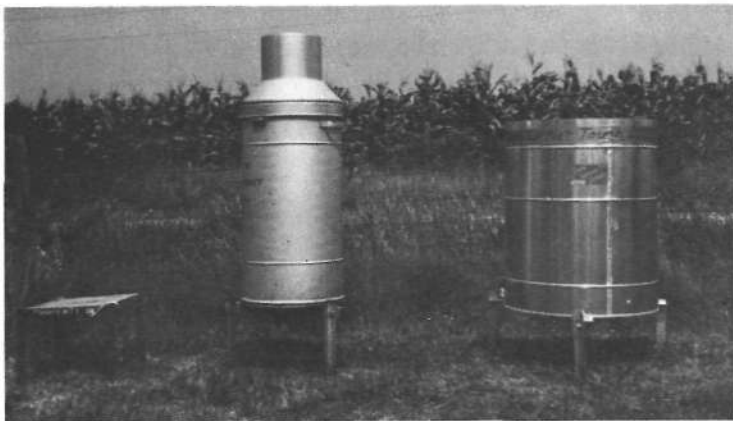
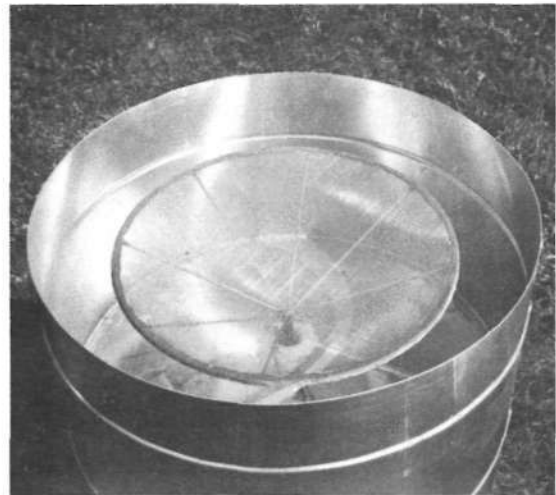


Figure 5. The 1969 array of hailgages and the Hailpad and Raingage Network during June-October





a. View of hailpad, recording raingage, and hailgage at site 106 with corn in the background



b. Close-up view of hailgage sensing platform at site 106



c. Installation at site 94. Raingage has enlarged collector (18-inch diameter) to magnify rainfall rate curve and hailspikes.



e. Hailgage at site 162 with outer cover and sensing platform removed. Soybean crop is in immediate background.



d. Raingage, windrecorder, hailgage (center foreground), hailpad, and plastic rainwater collector at site 136, corn on left and soybeans on the right

Figure 6. Various field sites of hailgages and associated instrumentation in Central Illinois during 1969

duties was to examine any crop-hail damages next to the hailgages as well as damages adjacent to the hailpads.

A field man performed a routine inspection of the 13 hailgages at least once a week during the 4.5-month operational period. Although no hailfalls, damaging or non-damaging, occurred during this period, behavior of the gages under prolonged field installation was carefully examined.

The weekly servicing of each hailgage requires 5 to 15 minutes depending on whether activated, and servicing consists of the following steps at each gage:

- 1) Turn off main system switch located on underside of hailgage to prevent starting hailgage while servicing.
- 2) Remove sensing platform and then lift off the outer cover.
- 3) Examine counterweights and battery wires, and check to see that drum gear is engaged with motor gear.
- 4) If gage has been activated between servicing:
  - a) Record clock time(s) and remove clock unit.
  - b) Disengage drive gears, remove data chart, and list date and time data.
  - c) Install new data chart, re-position the drum, and engage drive gears.
  - d) Reset clocks and re-install.
  - e) Reset control toggle switches.
- 5) Replace cover and sensing platform.
- 6) Turn system switch on.

The hailgages were removed from operation on 30 and 31 October 1969 and returned to the Water Survey. As time and funds permit, it is hoped to further

examine the wind problem and to install the windspeed recording apparatus that is desired for each gage. If funds are available, the gages will be reinstalled in the network for the March-September period of 1970.

#### Problems

A minor operational problem encountered was the occasional false start produced by human intervention (touching the sensing platform). A more important problem related to the initiation of gage operation by high winds (generally in excess of 30 mph). Upon investigation, it was discovered that during the adaptation of the prototype to the production gage the height of the outer cover had been decreased by inches. This was corrected by adding a 4-inch extension to the outer cover which prevents the eddies from impinging onto the gage top. The hailgage pictured in Fig. 6d has this extended outer shell, whereas the others in this figure were photographed during installation and do not have the higher rim. Thus, the only semi-major operational problem encountered during the non-hail period was the false starts of the gage with high gusts, and this problem appears to have been at least partially solved by the rim alteration. A less closely knit steel mesh on the sensing platform appears to be desirable for totally removing the wind effect.

## COMPARATIVE STUDIES OF OTHER HAILGAGES

### Background and Description of Study

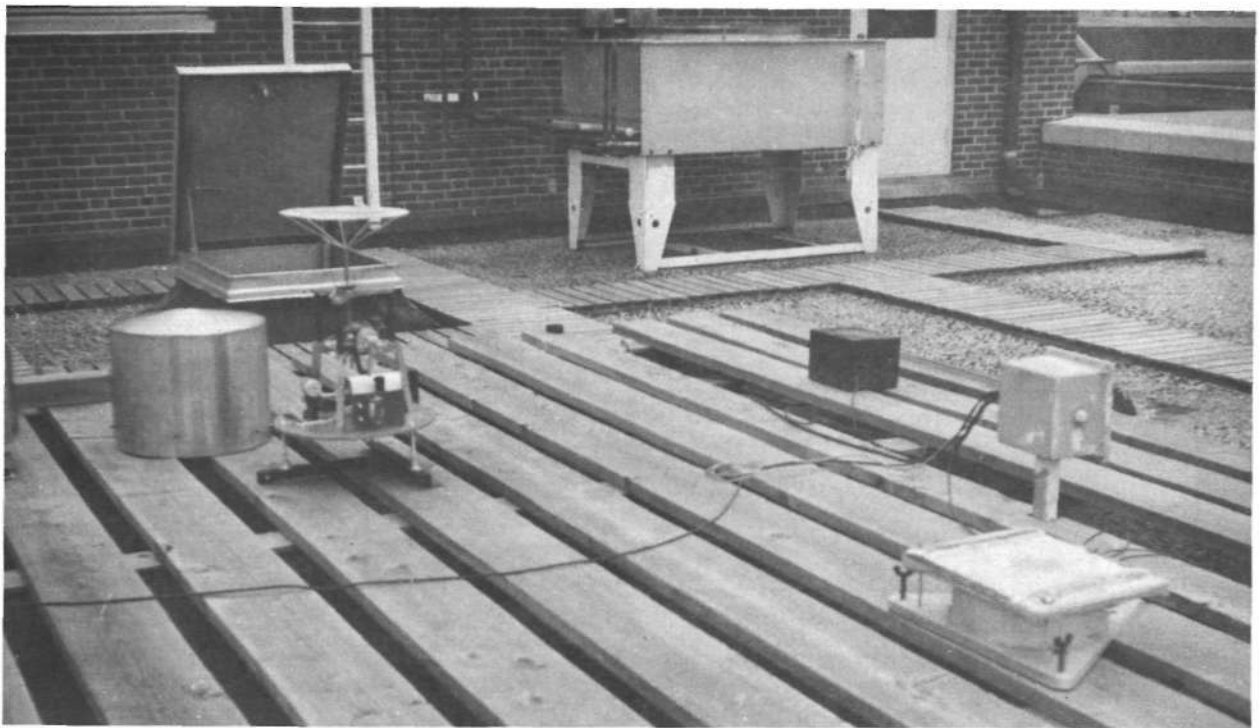
During 1966, when the Illinois hailgage design was being resolved, the South Dakota School of Mines and Technology also initiated work on another type of recording hailgage. Unlike the mechanical Illinois gage, this hailgage was based on electrical operations and was initially designed as a remote sensing device to telemeter hailfall occurrences to a radar station.<sup>8</sup> A few models of this hailgage had been completed and operated in South Dakota and Nebraska during the summer of 1968 with apparent success during two hailstorms.<sup>9</sup>

Also during the 1967-1968 period another form of hailgage, likewise based on electrical operations, was developed at the National Center for Atmospheric Research by Mr. Arden Buck under the direction of Dr. Guy Goyer. The prototype of this DPD (Design and Prototype Development) hailgage was completed during the late summer of 1968.

The hailfall characteristics measured on these and the Illinois hailgage are of interest and exhibit a compromise between furnishing practical answers such as hailfall energy or momentum that are relatable to crop or property damage, and scientific answers as to stone size, stone frequency, and type. However, these practical answers, whether they are momentum or energy, must be directly relatable to crop damage or they are meaningless for hail suppression evaluation. Studies of the relationships of momentum to crop damage should be pursued to fully establish this relationship. It is of interest to note that recording instruments that might give information most desired by many hail scientists, such as stone shape, water contents, and structure, have not been designed.

The availability of three different types of recording hailgages developed independently offered a unique opportunity to laboratory-test and field-test these instruments jointly. Therefore, the Illinois State Water Survey, which is located in an area with hailfalls in the fall, winter, and spring, undertook this joint testing program as a part of the Recording Hailgage Evaluation Project. The groups at NCAR and South Dakota sent their instruments to the Water Survey, in August 1968. These two instruments were mounted on the roof of the Water Survey Building where the Illinois prototype hailgage also had been installed during the summer of 1968. The NCAR DPD hailgage was interfaced to record hailstones on the chart of a Visicorder so that simultaneous records could be obtained. The NCAR hailgage also had provisions for recording this data on a tape recorder built into its base. Thus, all three hailgages, as shown in Fig. 7, were installed and operational during September, October, and November 1968. Unfortunately, no hailfalls occurred to provide test data.

The hailgages were removed from the roof-top installations in December and subjected to a series of laboratory tests. These tests consisted of the release of steel balls of varying size (0.25-inch to 1.5-inch diameter) from various heights to match the momentum and impact values for hailstones. The results obtained for the NCAR and South Dakota hailgages are described in detail in the following sub-sections of this report. The problems with the NCAR DPD hailgage led to the return of that instrument to NCAR during February 1969. The South Dakota hailgage was reinstalled on the roof of the Water Survey building during the March-May 1969 period for hail interception, but again no hail occurred. It was returned to South Dakota during June 1969.



a. (Left to right) The Illinois prototype hailgauge, the South Dakota gauge (black box), and the NCAR gauge (right foreground)



b. (Left to right) The South Dakota gauge, the NCAR gauge (with triangular base), and the Illinois gauge

Figure 7. The three recording hailgages as mounted on the roof of the Water Survey building during the fall of 1968

## South Dakota Geophone Hailgage

The operation and construction of the geophone hailgage are described in detail elsewhere.<sup>8,9</sup> Essentially, a hailstone impact on the device transfers momentum to a large mass. A geophone attached to the mass acts as a velocity transducer. Electronic circuits derive from the geophone output an electrical pulse whose amplitude is a function of the hailstone momentum. A recording of the instrument output indicates the time and the momentum for each hailstone impact.

Essentially, the geophone hailgage is designed to furnish a measurement that has a practical application and is presumably related to hail damage. The time distribution of stones and their size will be useful in assessing hail suppression efforts and the mesoscale storm characteristics.

The laboratory testing of this hailgage was performed during December 1968. The output of the geophone hailgage was recorded on two channels of a Visicorder with one channel set approximately ten times more sensitive than the other. The steel balls used to calibrate the geophone were held in place by an electromagnet with the voltage to the electromagnet recorded on a third channel of the Visicorder to indicate time of release.

The ball size and heights of fall used were chosen to match the momenta of hailstones falling at terminal velocity with a range of diameters from 0.25- to 2-inches. Air drag was neglected for drops of the balls, but this should be a very small error. Hailstone terminal velocity  $V$  was calculated from

$$v^2 = \frac{4 \rho_H g d}{3 \rho_A C_D}$$

where  $\rho_H$  and  $\rho_A$  are the densities of the hail and air, respectively;  $g$  is the acceleration of gravity;  $d$  is hailstone diameter; and  $C_D$  is the drag coefficient.

The choice of values for these is somewhat arbitrary, and the values used were:  $P_H = 0.85 \text{ g/cm}^3$ ,  $g = 908 \text{ cm/sec}$ ,  $p_A = 1.155 \times 10^{-3} \text{ g/cm}^3$  (20°C temperature, 80% relative humidity, and 700 ft elevation), and  $C_D = 0.6$ . This latter value, especially, might have been different. For perfect spheres with diameters in the region of interest (and up to 3 or 4 inches), and with terminal velocities appropriate to real hailstones (Reynolds numbers from about  $10^3$  to  $2 \times 10^5$ ), the drag coefficient is between 0.4 and 0.45. However, Macklin and Ludlam<sup>10</sup> suggest a constant value of  $C_D = 0.6$  as a more reasonable estimate of  $C_D$  for real hailstones (not perfect spheres). The measured density of the steel balls used was  $7.78 \text{ g/m}^3$ .

The range of momenta typical for real hailstones is from  $10^1 \text{ g/cm sec}^{-1}$  for 0.125-inch stones to  $10^6 \text{ g/cm sec}^{-1}$  for 4-inch stones. For 0.25- to 2-inch stones, the range of momenta is  $10^2$  to  $10^5 \text{ g/cm sec}^{-1}$ . The geophone gage was tested over approximately this range and the results are shown in Fig. 8. The diameter scale at the top is based on the assumptions used to calculate terminal velocities given earlier.

The output of the geophone is related approximately to the square root of the momentum of the impacting object. In spite of the curvature of the line (Fig. 8), the results of different diameter balls dropped from different heights indicates that this hailgage gave consistent results. For example, the six individual measurements averaged to get the 0.4963 inch deflection shown for the 0.875-inch steel ball dropped from 12 inches (less the diameter of the ball) were 0.494, 0.495, 0.494, 0.498, 0.496, and 0.501 inches. The worst of these is only 1% from the average, and measurement errors probably account for most of this variation. This reproducibility is a very desirable feature of the instrument.



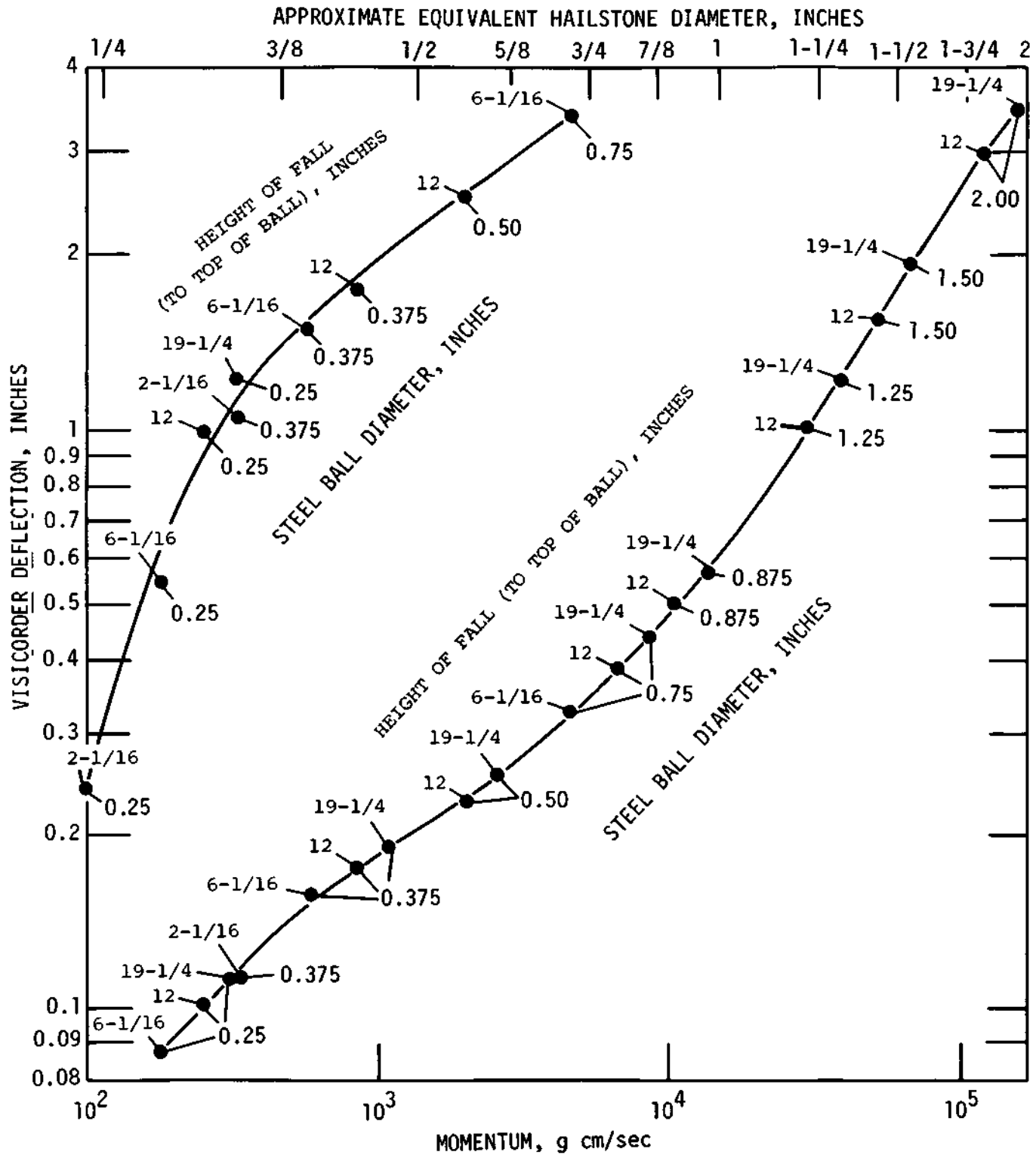


Figure 8. Calibration of Geophone hailage using steel balls and Visicorder recorder

A second desirable feature of the geophone gage is its minimum momentum sensitivity. It was capable of providing an output signal for the very small momenta associated with 0.25-inch hailstones. Although it was not tested below a momentum of about  $10^2 \text{ g cm sec}^{-1}$ , it probably would have detected lesser values, but perhaps not the order of magnitude less as required for 0.125-inch hailstones.

A final desirable feature, especially for use in the lee of the Rocky Mountains, is the ruggedness of the geophone. Since instrument damage or destruction was not desirable, our testing was limited to the equivalent momentum of a 2-inch hailstone. Nevertheless, a 2-inch steel ball dropped over 17 inches (19.25 inches minus 2 inches) certainly has some destructive capacity. The geophone would likely withstand most naturally occurring hailstones, especially if they deformed or broke upon impact (thus, internally absorbing some of their energies and thus momenta).

The small diameter of the sensing plate is a disadvantage. Since larger hailstones generally fall farther apart, the probability of one hitting such a small area is low.

In summary, the geophone hailgage appeared to be a device that:

- 1) gave a unique and reproducible output for each momentum value,
- 2) had good sensitivity at low momenta values,
- 3) covered the useful range of momenta,
- 4) should withstand most natural hailstorms without physical damage,
- 5) may somewhat misrepresent the true stone size distribution, especially for larger stones, because of its small sensing area.

In addition to the above, the following should be kept in mind for determining momenta of real hailstones. The momentum transferred to any momenta

measuring gage by a falling object, that is, a hailstone, is dependent upon the kind of impact experienced by the object, elastic or inelastic, and this cannot be known and must be assumed in any hailage data.

#### DPD Hailage of National Center for Atmospheric Research

The DPD hailage was a hail monitoring device which electrically indicated information about hail. The device was developed by the Design and Prototype Development (DPD) Facility at NCAR as a general field instrument which could be useful for other types of hail research including suppression evaluation. The device was designed to indicate: a) time of hail, b) number of hailstones per unit of time, c) impact energy, and by inference d) hailstone size.

The sensing element of the DPD hailage was a sheet of Butyl rubber, electrically shielded and attached to a heavy phenolic base. In response to a shock, the rubber produced a momentary abrupt increase in resistance. This resistance change was sensed as a voltage change and supplied the usable output.

The electronic portion of the instrument transformed the voltage pulse into a tone burst, the length of which was proportional to the original impact energy. The pulse was amplified, sharpened, and used to charge a capacitor. The capacitor in turn was allowed to discharge at a constant rate, giving a ramp function. The discharge time was then sensed by a comparator circuit, producing a gate pulse which allows a 4KC tone burst to appear at the output. The number of cycles in the burst indicated impact energy (response was compressed). The tone burst output was recorded directly on a small tape recorder, and output was also recorded on a Visicorder during the Illinois field operations and subsequent laboratory tests. In December 1968, an attempt was made to calibrate the DPD gage in the laboratory by using plastic and steel balls to simulate the effects of natural hailstones.

It was not known initially what the DPD hailgage responded to. It could have been energy, momentum, or some other characteristic of the impinging hailstone. A device (such as the aluminum covered, styrofoam hailpads<sup>7</sup>) which measures the energy of a falling hailstone must absorb that energy and stop the hailstone completely. The impacting steel balls (and plastic balls) were observed to bounce reasonably well from the DPD sensing platform, indicating that their energy was not being absorbed.

A momentum sensing device can respond to elastic and/or inelastic collisions (hailstones hitting and sticking). However, steel balls should not stick but should bounce, leaving with nearly the same magnitude of momenta they had upon arrival. A momentum sensing instrument needs to have a means of measuring the velocity of movement of the sensing surface. Since the DPD gage had a surface which reacts only at the area of impact, and that by compressing somewhat, it probably did not measure momenta.

The DPD hailgage might respond to the impulse of the steel ball (force times the time it acts) or to the pressure between the impacting object and the sensing material. Evaluation of the former requires a knowledge of the time it takes the object to strike and bounce, an unknown quantity with our calibration techniques. The latter explanation requires knowledge of the impacting area and the vertical stopping distance and/or the time of the action, again unknown. Since momentum and energy are easily calculated, the output of the DPD was compared with these quantities. In addition, because of the bouncing which took place, energy was later eliminated and all further comparisons were based on the momenta of the steel balls.

The calibration with steel balls was carried out to match the momenta and energies of real hailstones with diameters from 0.25- to 2-inches. In addition, plastic spheres with densities of about 0.8 to 0.85 g/cm<sup>3</sup> were dropped to simulate

hailstones. However, because of the uncertainties associated with their velocities (they did not reach terminal velocity but likely had been slowed by air drag), they were not used for the final evaluation. The range of momenta characteristic of real hailstones is about  $10^1$  to  $10^6$  g cm/sec (0.125- to 4-inch hailstones).

The results of the calibration with steel balls is shown in Fig. 9. Air drag was neglected for drops with the steel balls, but should amount to a small fraction of a percent error at most. The diameter scale at the top was obtained by using the same terminal velocity equation and same assumptions stated in the previous section on the geophone gage.

There is considerable spread in the points on Fig. 9. Possible explanations for this spread include: a) the instrument did not give the same output for all identical inputs; b) the surface characteristics changed from place to place on the pad; c) the output magnitude varied with time; and d) the ~~DD~~ hailgage does not measure momentum. This last point has already been mentioned, but it should be noted that a plot of the Visicorder output voltage against the wrong parameter would increase the scatter of the points. For example, the correlation coefficient between the momenta at impact and the output signal is 0.93 while the correlation between energy and output signal is less, 0.89. The first of the four explanations is certainly the cause of some variation. The rated accuracy of 20% should not, however, account for nearly the 0.8 of an order of magnitude spread in momenta values for a given deflection on the Visicorder record. Similarly, the surface characteristics should be uniform enough to contribute less than the rated 20% inaccuracy. Unfortunately, this might not be true as the imprints of earlier impacts were visible at various locations on the surface. In addition, the plastic waterproof covering of the Butyl was not smooth. This would absorb some of the

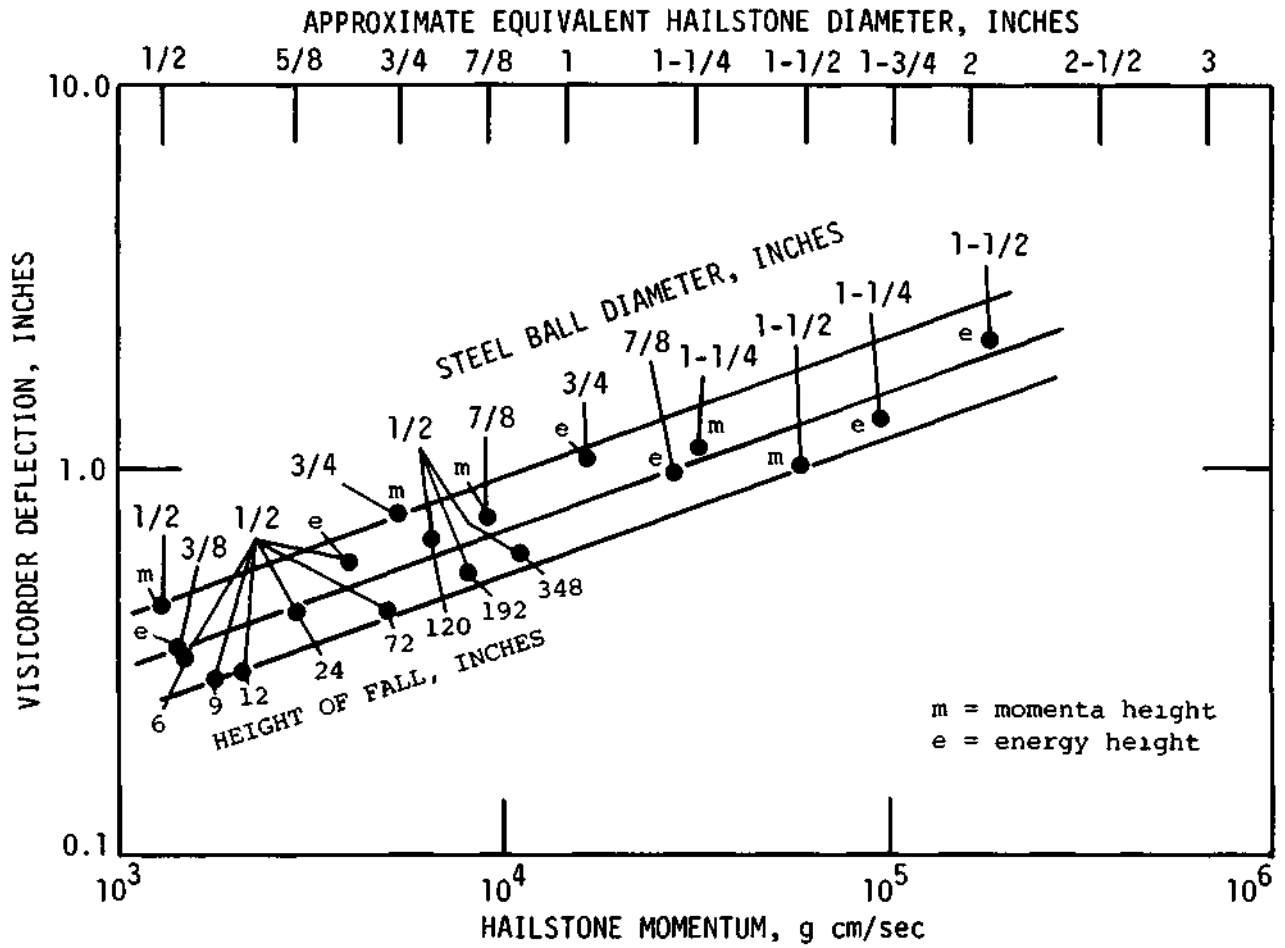


Figure 9. Calibration curve of the NCAR DPD hailgage obtained on Visicorder recorder using steel balls

energy of a falling sphere before it reached the sensor, a problem primarily of concern only for the smallest diameter spheres.

The most significant cause of error appears to be the time dependence of the output. Most calibration runs included from 2 to 6 consecutive drops of the same size ball from the same height. Initially, these values for a given size were averaged in the hopes of reducing "random" errors. A close inspection of the records revealed an apparent dependence of the output magnitude on the time between impacts.

Fig. 10 shows a plot of the ratio of the  $(i + 1)^{\text{th}}$  Visicorder deflection to the  $i^{\text{th}}$  Visicorder deflection against the time between impacts. Only those impacts which were of equal input momenta were used. That is, the plot is the ratio of output signals for equal input momenta. Those tracers which included bounces and noise or randomly triggered output signals between events were not used. Over 86% of all the pairs of impacts occurring within 30 seconds of each other indicate a second  $(i + 1)$  impact of smaller magnitude than the first  $(i)$  impact. Since this time dependence was not suspected before calibrating and our data did not adequately determine its causes and duration, further study is needed to resolve this problem.

A point to note regarding possible accuracy (Fig. 10) is that the three points with more than 30 seconds from any prior signal are all within 6% of the preceding input. Thus, the inaccuracy of the gage is likely on the order of at least  $\pm 6\%$ .

A point of significance for some areas of the world is that the DPD gage was completely insensitive to the impacts of spheres with a momentum less than that of 0.5-inch hailstone. Smaller momenta produced no output at all. For some applications this might be acceptable, but since 25% of the Illinois crop damage occurs with less than 0.5-inch hailstones, this minimum sensitivity

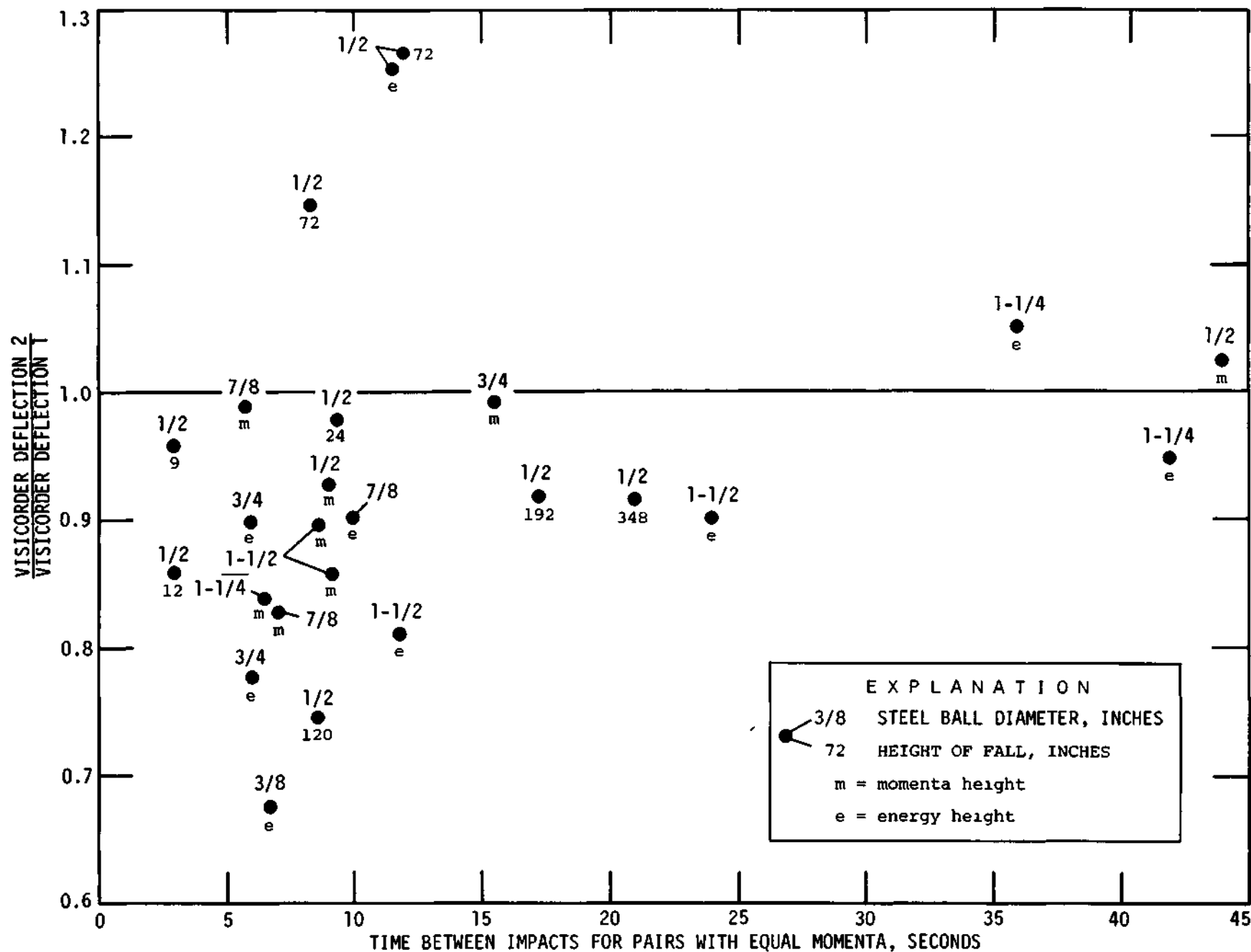


Figure 10. Time variation of the output of the NCAR DPD hailage



threshold could put severe limitations on the usefulness and application of the DPD hailgage in the Midwest. This threshold was adjustable to some extent, but for stable field operations, the adjustment would have to be such that the threshold would be even higher than 0.5-inch stones.

The DPD hailgage construction was sufficiently rugged to probably withstand the impact of any naturally occurring hailstones without incurring any physical damage. This is especially true if the larger stones would break or deform upon hitting, thus internally absorbing some of their energy. In regions with few small and many large hailstones, the DPD gage might prove quite useful because of this durability.

In summary its most serious problem was the apparent decrease of sensitivity of subsequent test impacts in rapid succession. The instrument was checked further in an electrical "quiet room," and scope waveforms indicated there was indeed a decrease in sensitivity depending on the intensity and time lapsed since the prior (ball) impacts. Also, it was noted the voltage regulators (used to provide a constant voltage from the battery pack) had an effective impedance high enough to cause problems in portions of the gage's electronics system. While observing the pad, it was noted that occasional random pulses occurred many seconds after a prior impact. These probably are the result of the electronics system faults that could be corrected. The Butyl recovery should be checked without the existing electronic circuitry. If the Butyl is usable as a sensor, then the electronics package needs to have the voltage regulator, threshold, and other items modified.

## COMPARATIVE STUDY OF HAILFALL PARAMETERS AND CROP LOSSES

The purpose of the hailgage evaluation project was to ascertain whether the hailfall data from these instruments could be related to actual crop loss values. Since 90% of the hail damage in the United States is to crops, it is only natural that hail research and hail suppression projects have attempted to obtain network type measurements of surface hailfalls that would be representative of crop loss. Since crops are often too sparse or a too non-uniform target in many areas, instruments that give objective measurements have become an immediate and obvious necessity for network oriented hail research programs in Illinois and the Great Plains.<sup>2</sup>

To gain some information of this type, since the hailgages did not experience any hail, data from passive 1-ft<sup>2</sup> foil-covered hailpads in the network<sup>7</sup> were compared with adjacent losses to crops in Illinois. The measurement of hailfall parameters using hailpads and hailgages raises three questions related to agriculture:

- 1) Do these instruments measure any hailfall condition that closely reflects crop loss?
- 2) If so, which of the parameters measured or estimated, such as energy, momentum, number of stones, and size of stones, are best related to crop damage?
- 3) Do these hailfall parameters that relate to crop loss differ between crop types and also differ during the crop growth season of a given crop?

One of the long-range goals of the Illinois hail research program has been to ascertain which of several hailfall conditions (hailstone size, number

of stones per unit area, energy, and associated winds) was most directly-related to crop-hail damage. Prior research using the cooperative observer data had indicated that neither stone size nor frequency were closely related to damage,<sup>11</sup> but the data were too qualitative to be totally conclusive. There is a need to establish the hailfall conditions that closely relate to crop loss so that proper values can be used from existing instruments and any existing or future equipment can be modified or designed to objectively measure losses in areas without crops or where crops are uninsured.

The operation in rural Illinois of 49 hailpads in a dense network in 1967 and 196 pads in a dense network during 1968 and 1969<sup>7</sup> has provided some useful quantitative data for studying this problem. In the 3-year period 34 different wheat losses ranging from 2 to 100% occurred within 100 feet of a hailpad. Hailpads were this near to 22 different corn losses, although unfortunately, the maximum loss measured close to a hailpad was only 25%. Hailpads also were close to 28 different soybean losses that ranged from 2 to 100%. The percentage losses were compared with eight forms of the data from their nearby hailpads. The total number of stones and duration of hail showed no relationship to the amount of loss, but total hailfall energy (or wind-driven effect) and total number of stones with diameters larger than 0.25 inch (or volume of ice) were related to loss, but in different ways. These results for the three crops, with the individual values designated by month so that any seasonal changes in the crop (as a target) could be assessed, are presented in Fig. 11.

Wheat losses had little relationship to hailfall energy with energies of 10.0 foot-pounds per square foot being associated with losses ranging anywhere from 4 to 100 percent. Similarly, all corn losses considered together show a poor relationship to energy, but if only the July-August data points are examined

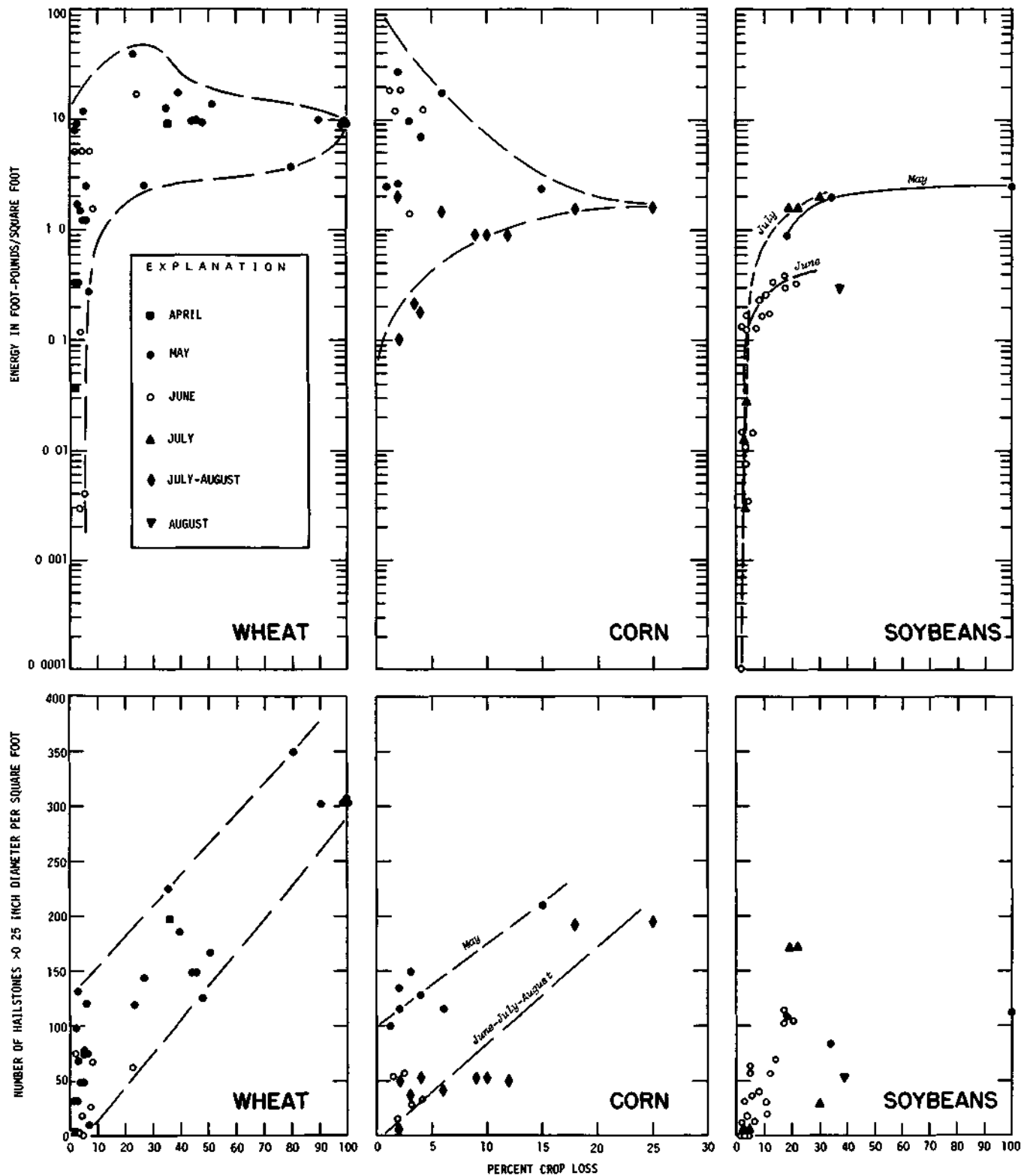


Figure 11. Comparison of crop loss with hail energy and frequency of hailstones with diameters >0.25 inch

(Fig. 11), an energy relationship is apparent. This results because wind-driven hail in July-August leads to stalk and ear damage as well as to defoliation. Hailfall energy does relate to soybean loss in all months. Three curves have been constructed for the soybean energy-loss data to conform to three apparently different seasonal relationships. The June data appear to fit a curve that indicates much less energy is needed in June to produce a 10-percent loss than is needed in May or July. This agrees with previous findings<sup>11</sup> that showed that soybeans have periods with greater susceptibility to loss in late June than exist in May or July.

The plot of wheat losses against the number of stones per square foot (a measure of the total volume of ice that fell) in Fig. 11, shows a fairly good relationship. Corn losses also show a marked relationship with the number of large stones. However, two stone-number relationships exist as noted by the two lines drawn in the graph for corn. The curve based on May data indicates that it takes more ice (stones) than in the June-August period to realize a corn loss. Hail volume in the June-August period is related to defoliation. This agrees with the susceptibility-to-damage results obtained for corn in earlier research which shows a distinct maximum in July.<sup>11</sup>

The results for soybean losses and number of stones (ice volume) do not agree with those for corn and wheat in that stone frequency does not relate well to loss. This indicates that hail damage to soybeans is largely a function of energy, or windblown hail.

These results show that crop loss is more closely related to amount of ice than to energy, although these data need to be corroborated and expanded with data from the hailgages. Importantly, they do indicate that one value, such as energy, can not be used to directly reflect crop loss potential (or effectiveness of hail suppression). Secondly, these limited results suggest

that for some crops, such as corn, the most important hail damage parameter may shift from volume of ice to energy. It is hoped that future hailgauge operations will provide useful data.

## SUMMARY AND RECOMMENDATIONS

When the need for a recording hailgage that could provide highly accurate time data for measurements of individual hailstone momenta or energy was established in 1966, design criteria were carefully established.<sup>7</sup> Decisions regarding availability of commercial power for gages in remote areas and the cost of gages based on principles of electrical operation led to a mechanical (ballistic pendulum) design for the Illinois hailgage.

The development of this gage, both the prototype and the 15 constructed under this project, has provided a field instrument that will reliably provide individual hailstone momentum data (plus size estimates) recorded against time. If produced in large numbers ( $> 100$ ) for network operations, its cost in 1969 dollars would be about \$260. Addition of a wind measuring device to record winds during hail would cost approximately \$20 and is considered to be a useful feature since windblown hail leads to certain forms of damage and is not properly measured with the hailgages.

Thus, a primary recommendation of this project is the addition of these wind recorders to each hailgage and subsequent field testing. Since the major research goal of the project, a comparison of gage-measured hail parameters against the degree of crop loss, was frustrated by the lack of hailfall at any gage in 1969, another recommendation is the future operation of these gages in field hail projects.

The costs of hailgages based on electrical operations have reduced significantly since 1966 due to miniaturization and mass production of new solid state devices. Thus, a hailgage designed in 1969 for electrical sensing, and capable of measurements comparable to the ballistic pendulum gage, might be less expensive. This alternative should be considered before any large numbers of the Illinois gage are constructed.

## SCIENTIFIC REPORTS AND PAPERS

The following reports were produced either wholly or partially as results from this project.

1. "Hail Measurements Techniques for Evaluating Suppression Projects" S. A. Changnon, Jr., published in J. Appl. Meteor., 8, 1969, 596-603.
2. "Hail Instruments and Hail Parameters That Cause Crop Damage" S. A. Changnon, Jr., presented at Eighth Agricultural Meteorology Conference, Seattle, Washington, September 10, 1969.
3. "Development of Hail Instruments" Seminar paper by S. A. Changnon presented at Chadron State College, Chadron, Nebraska on July 29, 1968.
4. "Illinois Hail Project and Its Equipment" Seminar paper by S. A. Changnon presented at Alberta Hail Project, Penhold, Alberta, July 30, 1968.



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